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VOLTAGE REGULATION

OF A

TRANSMISSION SYSTEM

BY

FREDERICK JOHN FOERSTERLING

B. S., UNIVERSITY OF ILLINOIS, 1911

THESIS

SUBMITTED IN PARTIAL FULFILLMENT
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I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

Frederick John Foesterling

ENTITLED VOLTAGE REGULATION OF A TRANSMISSION SYSTEM

BE ACCEPTED AS FULFILLING THIS PART ON THE REQUIREMENTS FOR THE

PROFESSIONAL DEGREE OF Electrical Engineer

Ellery B. Paine

Head of Department of Electrical Engineering

Recommendation concurred in:

C. R. Richards

Edward C. Schmidt

Committee

UIUC

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VOLTAGE REGULATION OF A TRANSMISSION SYSTEM

I.

INTRODUCTION

The maintenance of constant voltage at the lamps is of great importance. It is the measure by which the public judges the quality of the electrical illumination; because the life and candle power of the incandescent lamp change rapidly with a comparatively small change in voltage. It is therefore of vital importance that both the generator and feeder voltages be regulated automatically.

The object of this paper is to cover the development and the treatment of problems in voltage regulation met with in the growth and expansion of a conservatively operated central station located in a growing industrial city surrounded by the typical rural suburban towns and villages of Illinois. The central station dealt with is located at Peoria, Illinois, and its development undoubtedly closely parallels that of other central stations.

II.

HISTORICAL DEVELOPMENT OF THE GENERATING STATION

Peoria's first central station consisted of a small two phase 133 - cycle, belt-driven unit housed near the adjacent Illinois River. A few years later a second company was formed in a suburb. Although rather small and insignificant the first few years, the new company gradually secured a firm standing and eventually absorbed the original company. Little is known regarding the matter of voltage regulation in those early days. Electric light was so great an advance over the other available illuminants that no serious thought was given to the dimming of lights during certain hours of the day. When electric development reached the point where longer lines were necessary to feed districts more remote from the station, voltage regulation became a factor demanding consideration. It was found that by a proper distribution of districts on individual feeders and these supplied during the peak hours by different machines operated at voltages properly adjusted for each group, the problem was solved temporarily. The next step was to raise the voltage at the station on the longer feeders by means of boosters to supply the proper potential at the load center during peak hours. Originally the distribution system was designed for 1100 volt feeder voltage and 55 volt service. In a few years the voltages were changed to 2200 volts and 110 volts respectively. The large copper was a material aid in holding the proper potential at

out-lying points. With the growing load, the generators were soon called upon to take up load fluctuations without seriously affecting the station voltage.

The first attempt automatically to care for the fluctuations in the generator voltage brought out the compound field type generator. This method of generator voltage regulation was displaced by the Tirrill voltage regulator which is still in successful use. These, briefly, were the phases of development passed through before an adequate method of generator voltage control was secured. With stability of generator voltage established, it was necessary to restrict all work relative to voltage regulation to the individual feeders.

III.

CHANGES IN METHODS OF OPERATION NECESSITATED BY THE GROWTH AND EXPANSION OF THE BUSINESS

It was found that by connecting the compensating winding of the Tirrill regulator to the secondary winding of a current transformer, the primary winding of which was in series with a feeder, the load characteristics of which closely approximated the average conditions of all feeders, a fairly good regulation was obtained at the load center of each feeder. For several years emphasis was placed on the proper distribution of load on the primary feeders. The rapid expansion of electric service to nearby towns, as well as, the building up of out-lying dis-

tricts of the city soon made this method of regulation unsatisfactory.

In 1913 the entire generating station was rebuilt, and a new switch-board installed. At the same time voltage regulators were installed on all 2300 volt lighting feeders. This arrangement made it possible to operate with a constant bus voltage. After a thorough voltage survey of the city adjustments of the regulators were found where the regulation of the city as a whole was very good. Trouble was experienced on only one feeder which carried so great a load as to make it necessary to replace a section of the feeder with larger conductor.

The following year the transmission system was extended practically to its present limits. Due to unbalanced inductive conditions in the transmission system many telephone lines paralleling the system developed noises of so serious a nature as to make some useless. To eliminate these noises the circuit was stepped down to 2300 volts and up again to 13,200 volts at Farmington and Elmwood to supply towns beyond these points. It was soon discovered that the voltage regulation beyond these towns was very poor. To determine the causes and best methods of remedying this trouble necessitated a close study of the whole Western District transmission system. It eventually led to the successful solution of the whole problem. Confining ourselves to the regulation of the transmission system, it will be well to explain Plate I which shows the system as arranged when investigations began. A number of changes were made as will be shown later.

IV.

CONDITIONS LEADING TO POOR REGULATION IN THE TOWNS SUPPLIED FROM THE TRANSMISSION SYSTEM

Electric energy is generated three phase at the Peoria station at a constant bus voltage of 2300. In the nearby substation, through three 333 kv-a. General Electric transformers, this is stepped up three phase to 13,200 volts for the Pekin and Western districts. For the Western district energy is transmitted to Farmington, a distance of twenty-three miles, over a No. 2 B&S gauge copper line carried on a single cross arm with wires spaced 36 inches. Four miles from the substation a short spur feeds a 1000 ton capacity coal mine. At Maxwell four miles beyond this point a 10 kv-a. General Electric transformer supplies emergency single phase lighting service to a County Farm. Four miles beyond this at Hanna City a 1000 ton mine and the town are served, from three 100 kv-a. Westinghouse transformers. Continuing five miles further a 10 kv-a. General Electric transformer supplies single phase lighting to Trivoli. At the Farmington substation two General Electric transformers connected in open delta step down to 2300 volts three phase and supply all local three phase power and the residential lighting of the town. Connected across the remaining phase are two 50 kv-a. General Electric transformers in parallel stepping down to 2300 volts. This bank supplies Farmington's commercial lighting, a load of approximately 35 kw. and two 50 kv-a. General Electric

transformers which step up to 13,200 volts to supply the Farmington-Cuba transmission system. This system consists of a single phase line with No. 6 copper wire spaced 24" on a single cross-arm. Two miles out of Farmington a group of farmers are supplied with light and power from a 10 kv-a. General Electric transformer, three miles further west a 10 kv-a. Westinghouse transformer supplies Middle Grove, three miles further another 10 kv-a. Westinghouse transformer feeds Rapatee. Continuing six miles London Mills is reached where a 25 kv-a. Westinghouse transformer serves the town. Near Rapatee a branch extends south fifteen miles to Cuba. Five miles out of Rapatee a 25 kv-a. Westinghouse transformer supplies Fairview, five miles further a 10 kv-a. Westinghouse transformer feeds Fiatt. Cuba is served from a 50 kv-a. Maloney Transformer.

At the eastern extremity of Farmington a three phase branch is taken off leading to Elmwood, a distance of eight miles. This line consists of No. 4 copper arranged the same as the main line from Peoria. At Elmwood the current is stepped down to 2300 volts three phase through three General Electric transformers. One phase is again stepped up to 13,200 volts by means of a 50 kv-a. Maloney transformer to serve the Elmwood-Princeville transmission system, which consists of a single phase No. 6 copper line spaced 24". Six and a half miles out of Elmwood a 10 kv-a. General Electric transformer supplied a group of farmers. At Brimfield eight miles out a temporary bank of two transformers with a capacity of 25 kv-a. supplies the town.

Seven miles beyond this point Monica is fed from a 10 kv-a. General Electric transformer. Princeville at the end of the line, eighteen miles from Elmwood, is served from a 50 kv-a General Electric transformer.

The General Electric transformers in this district are type H, forms G 2, and G 3, primary volts 13200/22870 Y, with two 5% variable ratio taps, secondary volts 2300. All Westinghouse transformers are type SK, primary volts 13,200, with two 5% variable ratio taps, secondary volts 1100/2200.

The Maloney transformer at Cuba is a type A, primary volts 13200/12540 secondary volts 1100/2200, the one at Elmwood is similar except that it has two, 5 instead of 2 1/2% variable ratio taps.

With this arrangement the voltage regulation of the Western District was fair up to and including Farmington and Elmwood, but was very poor beyond these points. Basing our calculations on a small additional line drop to Princeville and Cuba, together with a transformer regulation based on ordinary transformer test values, the drop to the latter towns during the peak hours seemed abnormal. The decision was therefore reached to make a detailed test and a careful study of the Western District.

V.

TEST DATA OF TRANSMISSION SYSTEM GROUPS AND A COMPARISON OF SAME WITH CALCULATED DATA

TABLE I.

ELMWOOD-PRINCEVILLE TRANSMISSION SYSTEM TEST DATA

AUGUST 7, 1915

Time PM	Delivered to System at Elmwood: On 2200 Volt Side of S.S. Step-up Transformer I	E	W	V.A.	P.F.	On 13200 V.Side E	Received from System at Princeville: On 13200 V.Side E	On 2200 Volt Side of S.S Step-down Transformer I	E	W	V.A.	P.F.	Received from System at Country Line S.of Brimfield & Loss: Brimfield W	Monica W	Country Line S.of Brimfield & Loss W
6:40	14.52	2304	11400	33453	34.1	14160									
7:00							13716	5.64	2510	7800	14150	55.6			
7:10							13536	7.26	2470	13200	17770	74.3			
7:30	22.20	2260	43800	50150	87.2	13368		9.90	2266	19320	22450	86.1	14730	2880	6870
:35	29.22	2232	57240	65250	87.7	12960	12660	15.72	2266	31200	35621	87.5	14980	2960	8100
:40	29.58	2222	58040	65400	88.8	12900	12660	15.72	2246	31236	35307	88.6	15200	3040	8564
:45	29.88	2210	58440	66100	88.4	12852	12540	16.14	2246	31956	36210	88.2	15600	3040	7854
:50	29.58	2210	57480	65300	87.8	12840	12540	16.14	2246	31596	36210	88.2	15840	3040	7004
:55	29.48	2196	59040	64730	88.2	12744	12540	15.78	2246	31596	35400	90.2	19900	3120	4424
8:00	32.64	2188	64080	71450	89.7	12660	12432	16.14	2224	32208	35876	89.8	18240	2960	10572
:05	24.78	2200	59640	67700	88.2	12744	12432	15.90	2224	21716	25400	89.7	20400	2960	4564
:10	32.64	2190	64080	71500	89.7	12660	12432	16.14	2224	32328	35876	90.5	20550	2800	8402
:15	32.64	2180	64080	71200	90.0	12660	12432	10.02	2224	32088	35680	89.9	19780	2640	9572
:20	30.96	2190	59880	67900	87.9	12720	12432	16.32	2224	32448	36302	89.4	18000	2640	6792
:25	32.52	2186	62880	71200	88.3	12660	12432	15.66	2224	31596	34804	90.6	21200	2640	7444
8:30	32.52	2188	63380	71250	88.9	12660	12432	15.42	2224	31224	34300	91.0	20700	2400	8056
:35	31.16	2186	62640	70420	89.1	12696	12432	15.60	2224	31104	34764	89.5	20250	2160	9126
:40	30.48	2190	58440	66680	87.5	12720	12432	15.60	2224	30864	32582	91.4	17120	2160	8296
:45	28.74	2210	55440	63510	87.2	12840	12600	14.52	2246	29760	34068	85.7	17500	2160	6020
:50	28.92	2210	55500	63980	86.9	12840	12540	15.82	2234	29640	34394	88.4	20000	2160	3700
:55	31.68	2190	61680	69460	88.8	12720	12432	15.42	2224	30372	34934	88.4	20950	2080	8278
9:00	31.38	2200	61680	69000	89.4	12720	12432	15.42	2224	30372	35057	87.4	20000	2080	9228
3:00 A.M. 8/8/15		2400							2610						

TABLE II.

ELMWOOD-PRINCEVILLE TRANSMISSION SYSTEM VOLTAGE REGULATION DATA

FROM TEST OF AUGUST 7, 1915

Time PM	At Elmwood On 2300 Volt	At Elmwood On 13200 Volt	At Princeville On 13200 Volt	At Princeville On 2300 Volt
6:40	4.0			
7:00			4.1	
7:10			5.3	5.4
7:30	5.8	7.2		13.2
7:35	7.0	10.0	11.5	13.2
7:40	7.4	10.4	11.5	14.0
7:45	7.9	10.7	12.3	14.0
:50	7.9	10.8	12.3	14.0
:55	8.5	11.5	12.3	14.0
8:00	8.9	12.1	13.1	14.8
:05	8.3	11.5	13.1	14.8
:10	8.8	12.1	13.1	14.8
:15	9.2	12.1	13.1	14.8
:20	8.8	11.7	13.1	14.8
:25	9.0	12.1	13.1	14.8
8:30	8.9	12.1	13.1	14.8
:35	9.0	11.8	13.1	14.8
:40	8.8	11.7	13.1	14.8
:45	7.9	10.8	11.9	14.0
:50	7.9	10.8	12.3	14.4
:55	8.8	11.7	13.1	14.8
9:00	8.3	11.7	13.1	14.8

TABLE III.

FARMINGTON-CUBA TRANSMISSION SYSTEM TEST DATA

SEPTEMBER 11, 1915

Time PM	Delivered to System At Farmington			Received from System 2300 Volts at							Middle Grove Rapatee Fiatt & Loss in Watts
				London Mills		Fairview		Cuba			
	Watts	Volts	Volts	Watts	Volts	Watts	Volts	Volts	Volts	Watts	
8:05	89300	2320	13140	14400	2240		2060	12540	2050	37750	
:10	89300	2320	13140	15360	2240	19100	2080	12540	2050	37750	17090
:15	90700	2320	13140	16800	2250	18800	2080	12540	2050	36500	18600
:20	89800	2320	13140	16480	2260	19680	2090	12540	2050	35850	17790
:25	87400	2320	13080	16960	2270	19100	2090	12540	2050	35200	16140
8:30	87400	2320	13080	17110	2280	18800	2090	12540	2050	35600	15890
:35	88300	2325	13080	16960	2280	19830	2100	12600	2060	35850	15660
:40	88800	2325	13080	16630	2280	18500	2110	12600	2060	41000	12670
:45	88300	2325	13080	16480	2280	19100	2120	12480	2020	41000	11720
:50	89800	2330	13140	16480	2280	17600	2130	12480	2020	41000	14620
:55	89300	2335	13200	16800	2290	17600	2130	12480	2020	41000	13900
9:00	88800	2340	13260	16630	2290	17600	2140	12480	2020	41000	13570
3:00 A.M. 9/12/15		2540	14580		2430		2420	14520	2420		

TABLE IV.

FARMINGTON-CUBA TRANSMISSION SYSTEM VOLTAGE REGULATION DATA

FROM TEST OF SEPTEMBER 11, 1915

Time PM	Per cent Drop in Voltage At					
	Farmington		London Mills	Fairview	Cuba	
	2300 V.	13200 V.	2300 V.	2300 V.	13200 V	2300 V.
8:05	8.7	9.9	7.8	14.9	13.6	15.3
:10	8.7	9.9	7.8	14.0	13.6	15.3
:15	8.7	9.9	7.4	14.0	13.6	15.3
:20	8.7	9.9	7.0	13.6	13.6	15.3
:25	8.7	10.3	6.6	13.6	13.6	15.3
8:30	8.7	10.3	6.2	13.6	13.6	15.3
:35	8.5	10.3	6.2	13.2	13.2	14.9
:40	8.5	10.3	6.2	12.8	13.2	14.9
:45	8.5	10.3	6.2	12.4	14.1	16.5
:50	8.3	9.9	6.2	12.0	14.1	16.5
:55	8.1	9.5	5.8	12.0	14.1	16.5
9:00	7.9	9.1	5.8	11.6	14.1	16.5

Note:

The voltage at 3:00 A.M. 9/12/15, in each town was used as basis of calculation.

TABLE V.

DISTRIBUTION OF PEAK PERIOD LOAD

WESTERN DISTRICT

Town or System	K.W.	K.W
Hanna City		10
Trivoli		6
Farmington		80
Farmington - Commercial	35	
Farmington - Residential	45	
Farmington - Cuba System		89
Farmers	3	
Middle Grove	3	
Rapatee	3	
London Mills	17	
Fairview	19	
Fiatt	3	
Cuba	41	
Elmwood System		85
Elmwood-Princeville System		60
Brimfield	20	
Monica and Farmers	8	
Princeville	32	
Total		330
Pekin System		330
TOTAL		660

TABLE VI

TRANSMISSION LINE DROPS CALCULATED FROM FORMULAS

$\delta = 3\ I\ (R \cos \phi + X \sin \phi)$ Per mile of line for 3 phase
$\delta = 2\ I\ (R \cos \phi + X \sin \phi)$ " " " " " 1 phase

POWER FACTOR = 90%

Section of Line	Miles	No. Phases	Wire Size	Spacing Inches	K.W. Load	E	Ia+ 100%P.F.	R cos Ø	X sin Ø	Volts Drop	% Drop
Peoria-Farmington	23	3	2	36	330	12900	14.80	0.74	0.30	613	4.64
Farmington-Elmwood	8	3	4	36	145	12600	6.65	1.18	0.31	138	1.10
Elmwood-Brimfield	8	1	6	24	60	12700	4.72	1.92	0.29	167	1.31
Brimfield-Princeville	10	1	6	24	34	12400	2.74	1.92	0.29	121	0.98
Farmington-Rapatee	8	1	6	24	88	12700	6.93	1.97	0.29	229	1.80
Rapatee-London Mills	6	1	6	24	17	12600	1.35	1.92	0.29	36	0.29
Rapatee-Fairview	5	1	6	24	63	12200	5.16	1.92	0.29	114	0.93
Fairview-Cuba	10	1	6	24	43	11900	3.61	1.92	0.29	160	1.34

TABLE VII.

VOLTAGE REGULATION OF SUBSTATION TRANSFORMERS

WESTERN DISTRICT

Location	Function	Make	Ratio	Kv-a Rated	Kv-a as Connected	Kw Test Load	Regulation 100% Rated Kv-a. 100%P.F.	Regulation 100% Rated Kv-a. 90%P.F.	Regulation Test Load 90% P.F.
Peoria	Step-up	Gen.Elec.	5.74	333	333	220	0.52	1.25	0.55
Elmwood	Step-down	"	5.46	50	47.5	60	1.23	2.29	3.66
Elmwood	Step-up	Maloney	6.00	50	50	60	1.00	2.30	3.31
Princeville	Step-down	Gen.Elec.	5.46	50	47.5	32	1.23	2.29	1.04
Farmington	Step-down	"	5.17	50	45.0	62	1.23	2.29	4.35
Farmington	Step-up	"	5.74	50	50	45	1.23	2.29	1.86
London Mills	Step-down	West.	6.00	25	25.0	17	1.30	2.40	1.11
Fairview	Step-down	"	6.00	25	25.0	19	1.30	2.40	1.39
Cuba	Step-down	Maloney	6.00	50	50.0	41	1.00	2.30	1.55

TABLE VIII.

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TABLE VIII.

COMPARISON OF CALCULATED AND ACTUAL VOLTAGE REGULATION AS FOUND UNDER TEST THROUGHOUT WESTERN DISTRICT UNDER PEAK LOAD

Town	Circuit	Cause of Drop	Calculated Drop	Test Drop	Remarks
Peoria	2300		0	0	From Bus
		Peoria Step-up Trans.	0.55		
		Peoria-Farmington Line	4.64		
Farmington	13200		5.19	5.0	Test drop from chart taken 9/18/15
Farmington	13200		5.19		
		Farmington Step-down Trans.	4.35		
Farmington	2300		9.54	8.66	Test drop from calculations and chart taken at substation 9/11/15
Farmington	2300		9.54		
		Farmington Step-up Trans.	1.86		
		Farmington-London Mills line	2.09		
		London Mills Step-down Trans.	1.11		
London Mills	2300		14.60	13.5	Test drop from chart taken at substation 9/10/15
Farmington	2300		9.54		
		Farmington Step-up Trans.	1.86		
		Farmington Fairview line	2.73		
		Fairview step-down Trans.	1.39		
Fairview	2300		15.52	14.48	Test drop from chart taken at substation 9/11/15
Farmington	2300		9.54		
		Farmington Step-up Trans	1.86		
		Farmington-Cuba line	4.07		
		Cuba step-down Trans.	1.55		
Cuba	2300		17.02	16.50	Test drop from chart taken at substation 9/11/15
Peoria	2300		0		
		Peoria step-up Trans.	0.55		
		Peoria-Elmwood line	5.74		
		Elmwood Step-down Trans.	3.66		
Elmwood	2300		9.95	8.33	Test drop from readings and chart taken at substations 8/7/15
Elmwood	2300		9.95		
		Elmwood Step-up Trans.	3.31		
		Elmwood-Princeville Line	2.29		
		Princeville Step-down Trans.	0.94		
Princeville	2300		16.49	14.94	Test drop from readings taken 8/7/15 at substation and from chart taken 8/7/15 at customer's cut out

The Elmwood-Princeville line was tested and studied first. On June 25, 1915, all substation transformers were cut off this line, the two wires connected at Princeville, and the resistance of the line determined from Elmwood and found to be 79.5 ohms. This was several per cent higher than previous calculations led us to expect. Later it was discovered that the line contained a length of iron wire. This together with the fact that the line had some poor joints and had been up five years, in which time the cross-section of the wire had probably decreased slightly due to strains, explained the deviation from the calculated value. On the evening of August 7, 1915, simultaneous readings of amperes, volts and watts on the 2300 volt side and the volts on the 13,200 volt side were taken at Elmwood and Princeville, and the watts determined on the 2300 volt side at Brimfield and Monica by timing the substation watthour meters. The results of this test and the calculations derived therefrom are shown in Tables I and II. Fig. 2 shows the voltage on the 2300 volt side at Elmwood before stepping up for transmission over the Elmwood-Princeville line. Fig. 3 shows actual conditions as found at customer's cut out in Princeville in August, 1915. The results of the test were a surprise, but so interesting that the Farmington-Cuba system was also tested. Tables III and IV show the results of this test. Figs. 4 to 11 inclusive show graphically the voltage conditions of this system in September, 1915.

With the test data of the Western District at hand Tables V and VI were compiled. Table VII was compiled from data

largely furnished by the manufacturers of the transformers in use. From these tables it can readily be seen why the voltage regulation was found poor beyond Elmwood and Farmington.

Comparing the results of the tests as found in Tables II and IV with the calculated values shown in Tables VI and VII, it is to be noted that in all cases the calculated values are the higher. This is partly due to the method of calculating the drop from the test data; the light load voltage of the town under discussion being used as a base for calculations having reference to that town. Thus the voltage drop under light load at a town is not taken into account in calculating its regulation. This seems proper, because it is only the actual change in voltage which must be compensated for, since exciting current must be supplied to transformers and meters at all times, and it is this exciting current which causes the greater part of the initial drop. Test values shown in Table I compared with values calculated from the ratios shown in Table VII show this drop to be approximately 0.8% to Farmington and Elmwood and nearly as much more from these points to Cuba and Princeville respectively. With a large number of extremely old transformers on the lines of the Western District at the time of test this value is difficult to check. Comparing the individual per cents of drop calculated from the test with the theoretical values, the following may be noted.

Taking into account the light load drop of 0.8% at Elmwood, the 9.0% regulation found on the 2300 volt side at Elmwood

checks within 0.2% of the theoretical value. The step-up transformer regulation checks within 0.4% of the theoretical. Table VI calls for 2.29% drop in the line from Elmwood to Princeville while the test value averages slightly above 2.0%. With reference to this it must be appreciated that in order to secure the exact drop in a line under test with instruments at each end the readings must be taken at exactly the same instant as fluctuations of 1% occur continually. The regulation of the Princeville step-down transformer as determined under test must be in error approximately 0.7%. This must be attributed to an instrument or potential transformer ratio error.

Proceeding in the same manner with the Farmington-Cuba system data taken under test Saturday evening September 11 and 18, 1915, a light load drop of 0.8% at Farmington is to be noted from Tables III and VII. This appears not far from correct. The 8.7% drop on the 2300 volt side at the same point under load consists of 4.6% line drop and 4.1% transformer regulation. Table VII calls for a drop of 1.86% in the step-up bank agreeing with the test value. The test value of drop recorded at London Mills on the evening of the test can not be correct, as it is less than that at Farmington, the source of supply. The probable cause of this discrepancy was the production of an abnormal condition through the presence of the inspector on the substation pole, and a consequent interference with free pen action on the chart. This assumption is borne out by the previous day's chart, reference to which shows a drop of 11.5%. On the evening of

the test the drop at this town should have been approximately 3.2% more than at Farmington, or 14.6%. The theoretical drop at Fairview is 15.5% while the test value derived is 13.6%. The discrepancy of 1.9% must be attributed largely to the light load drop in voltage at this point. A slightly better regulation in the step-down transformer than was assumed, together with instrument errors, probably accounts for the remainder. At Cuba the test value agrees very closely with the theoretical value. The regulation of the step-down transformer as calculated from test values is somewhat higher than shown under Table VII, which is probably due to instrument errors. Table VIII shows the voltage regulation at the various towns of the Western District both as calculated and as found.

VI.

RECOMMENDATIONS MADE BY AN ELECTRICAL MANUFACTURER FOR THE IMPROVEMENT OF THE VOLTAGE REGULATION

The recommendations of one large electrical manufacturer for the proper voltage regulation of the two systems called for five automatic feeder voltage regulators, three on the Farmington-Cuba, and two on the Elmwood-Princeville system. 25 ampere, 5 3/4 kv-a. regulators were recommended for Cuba and Princeville and 10 ampere, 2.3 kv-a. for Fairview, London Mills and Brimfield, all to be designed for 10% lower and 10% boost. It was also recommeded that all regulators be protected from high voltage disturbances by: (1) Aluminum arresters at the substa-

tions; (2) Aluminum by-pass cells shunting the series coils of the regulators; (3) A choke coil in each lead on the load side of the regulators; and (4) Graded shunt resistance multigap arresters on each feeder. A quotation on this equipment exclusive of freight, installation or protective apparatus was $1775. The freight installation and protective equipment was estimated at an additional $394, thus bringing the total cost to $2169. These recommendations were made with the assumption that the two step-down and step-up banks of transformers at Farmington and Elmwood were to be removed from the systems after the telephone companies had reconstructed their circuits to eliminate inductive noises.

VII.

PLAN ADOPTED

The plan adopted was to continue stepping down and up at Farmington and Elmwood and insert on the 2300 volt side at each of these points on automatic feeder voltage regulator equipped with a line drop compensator and of sufficient capacity to handle the load beyond these points. A 50 ampere 11 1/2 kv-a. regulator was found to be ample for the service at each location. These were purchased at a cost of approximately $1100. Freight, installation, slight additional protective apparatus and line drop compensators arranged for both resistive and reactive drop added $100, thus making the total cost $1200. With this arrangement it was found unnecessary to purchase elec-

trolytic arresters as the substations at these points were equipped with same. This plan reduced the number of regulators from five to two and not only regulates the five most important towns, but also regulates six other small installations and is of sufficient capacity to handle several more small installations should they be connected. The fact that both regulators are now at easily accessible points and at the same time at fairly important centers of distribution where is is necessary to maintain a trained corps of men at all times, is another important factor favoring this arrangement. As no regular men are maintained at Fairview, London Mills and Brimfield, the installation of regulators at these points would have meant an increase in operating expense. The two regulator plan thus reduced the first cost $969, reduced the possible sources of trouble from five to two and regulates the two systems in their entirety. It might be added that recently the Illinois State Public Utilities Commission upheld the contentions of the telephone companies about Farmington and the maintenance of transforming equipment at this town for the Farmington-Cuba circuit was made compulsory on the part of the central station. The transformer banks at both Farmington and Elmwood have been replaced with equipment of greater capacity as the tests showed an overload at both points. Farmington is now supplied from three General Electric 50 kv-a. transformers independently of the Farmington-Cuba transmission system. The latter system is supplied from two 200 kv-a. General Electric transformers, one stepping down and the other up. These transformers are larger

than necessary, but being in stock were used to avoid buying new equipment. Elmwood is supplied independently of the Elmwood-Princeville line through three 50 kv-a. General Electric transformers. The Elmwood-Princeville and the Yates City-Maquon systems were combined and are supplied from two 50 kv-a. General Electric transformers in parallel stepping down to 2300 volts for voltage regulation. Two 30 kv-a. General Electric transformers in parallel step up for the Elmwood-Princeville system. Yates City is supplied 2300 volts directly from the regulator. A 30 kv-a. General Electric transformer at Yates City steps up the circuit to 13200 volts for the Maquon Line.

VIII.

RESULTS OBTAINED FROM THE VIEWPOINT OF SERVICE RENDERED SHOWING ACTUAL VOLTAGE CHARTS TAKEN BEFORE AND AFTER THE INSTALLATION OF REGULATORS

Reference to Figs. 12 to 24 inclusive shows at once how satisfactorily the arrangement is operating. These charts show voltage conditions as found over the two systems in March and April, 1916, after the two regulators had been installed and the above mentioned changes made. While these charts show that the matter is well in hand, there still remains some work to be done. It is to be noted in Fig. 16 that approximately 4.3% drop occurred at customer's cut out at Cuba on Saturday evening, March 11, 1915, which did not occur on the following Monday evening. This is explained by the fact that on the evening of March 11,

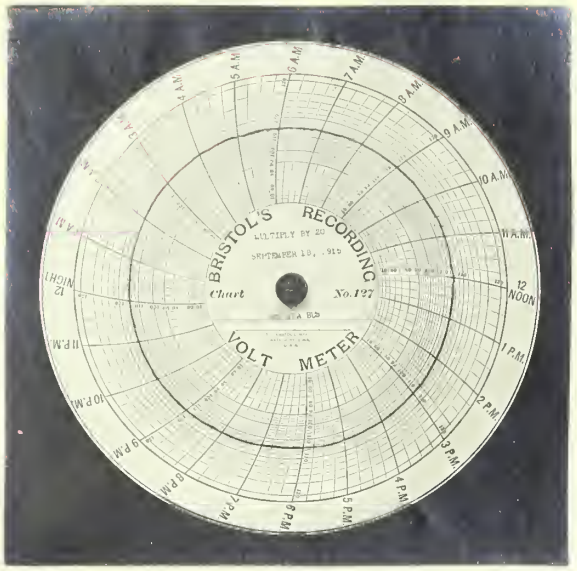

BRISTOL'S RECORDING
MULTIPLY BY 25
SEPTEMBER 18, 1915
Chart No. 127
VOLT METER
5 A.M.
6 A.M.
7 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT

Fig. 1

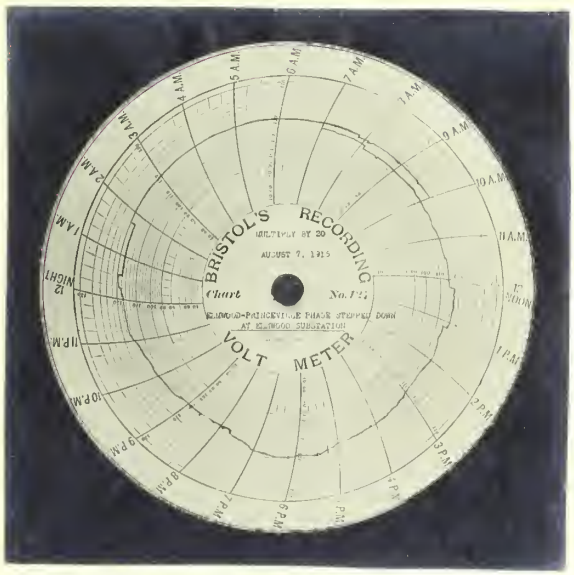

BRISTOL'S RECORDING
MULTIPLY BY 20
AUGUST 7, 1915
Chart No. 124
VOLT METER
5 A.M.
6 A.M.
7 A.M.
9 A.M.
10 A.M.
11 A.M.
1 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.
4 A.M.

Fig. 2

VOLT METER

Fig. 3

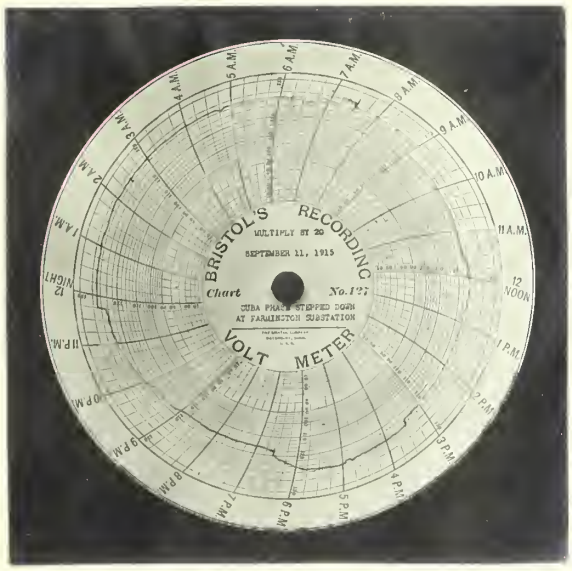

BRISTOL'S RECORDING
MULTIPLY BY 20
SEPTEMBER 11, 1915
Chart No.127
CUBA PHASE STEPPED DOWN
AT PARAMINTON SUBSTATION
VOLT METER
4 A.M.
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 MIDNIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 4

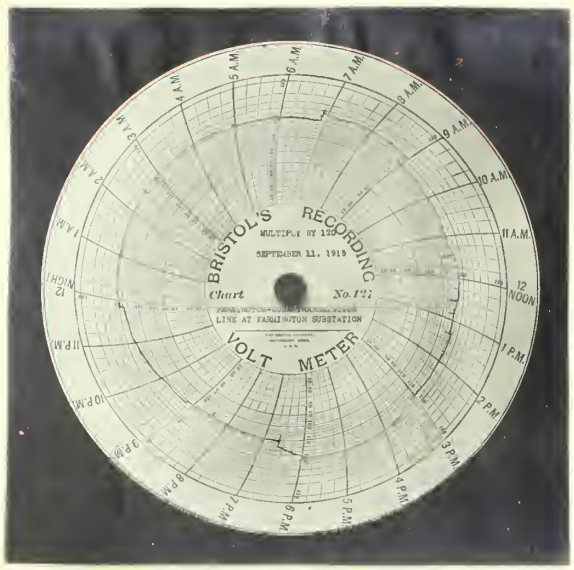

BRISTOL'S RECORDING
VOLT METER
Chart
4 A.M.
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 MIDNIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 5

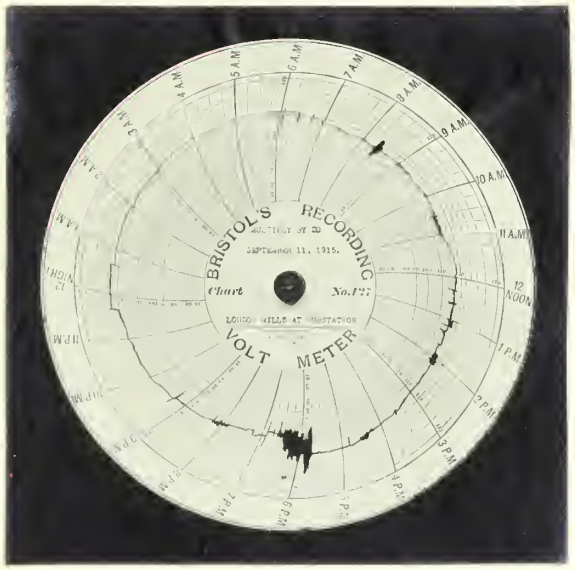

BRISTOL'S RECORDING
VOLT METER
Chart
4 A.M.
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.

Fig. 6

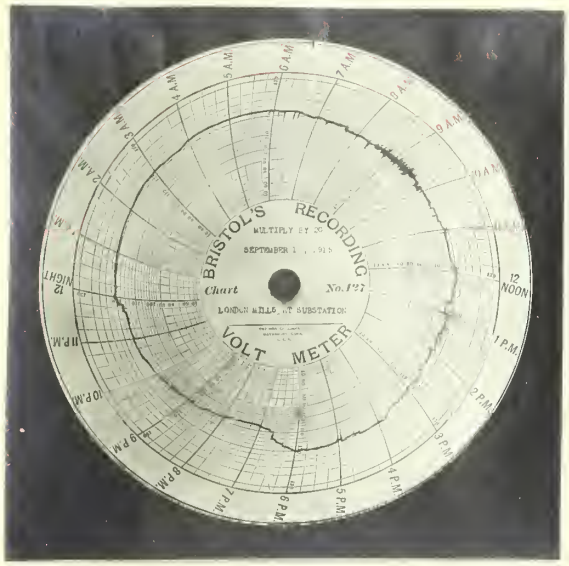

BRISTOL'S RECORDING
VOLT METER
Chart
No. 127
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.
4 A.M.
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.

Fig. 7

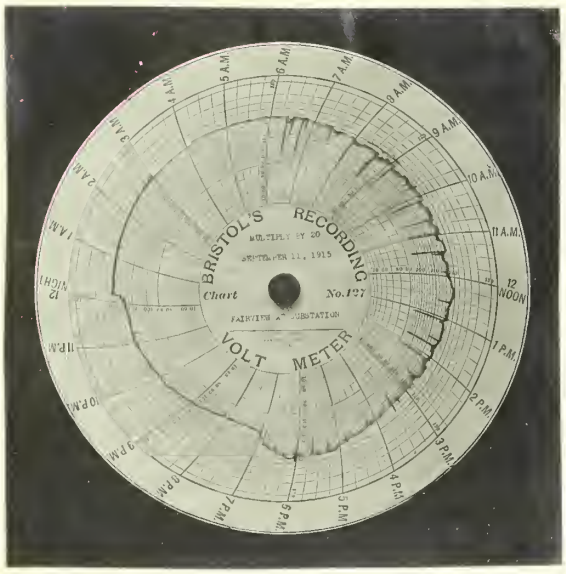

BRISTOL'S RECORDING
VOLT METER
Chart
No. 127
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.
4 A.M.
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.

Fig. 8

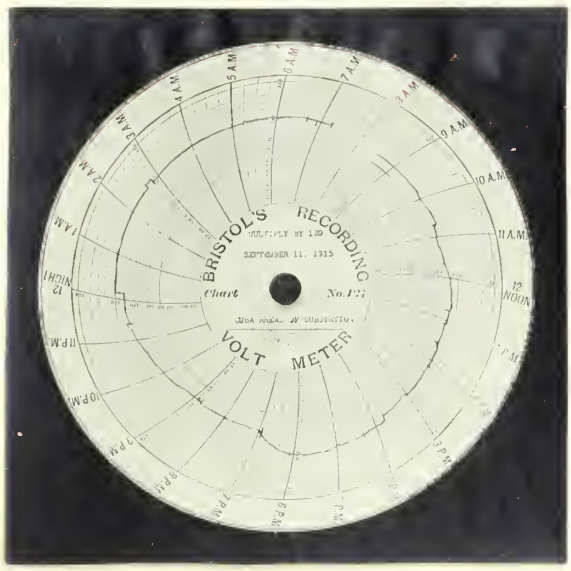

BRISTOL'S RECORDING
VOLT METER
SEPTEMBER 11, 1915
Chart
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.
4 A.M.

Fig. 9

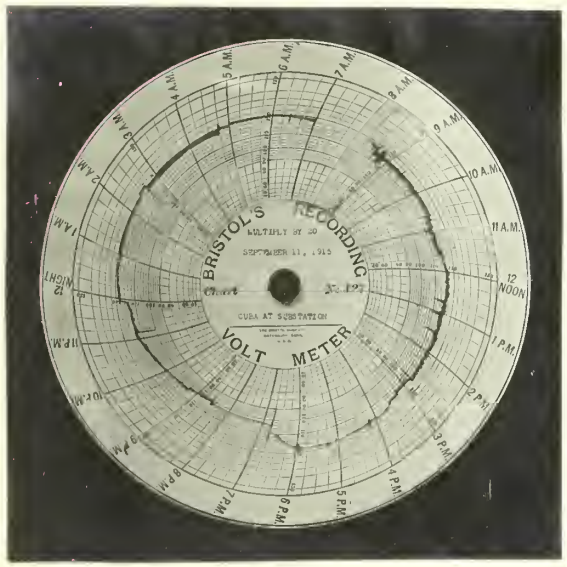
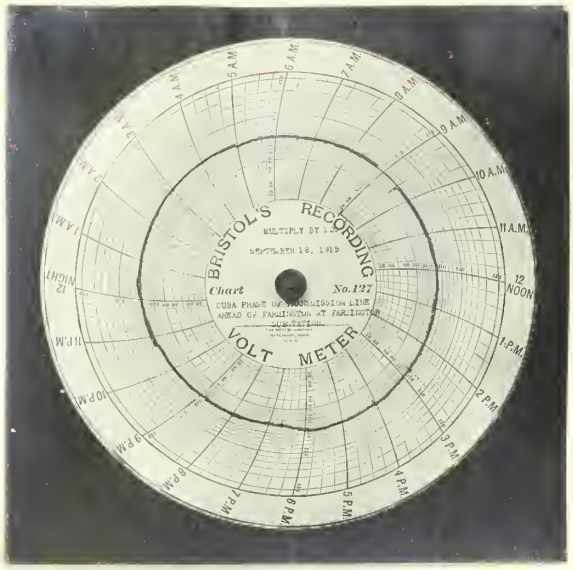

BRISTOL'S RECORDING
VOLT METER
SEPTEMBER 11, 1915
CUBA AT SUBSTATION
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.
4 A.M.

Fig. 10


BRISTOL'S RECORDING
VOLT METER
Chart
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4 A.M.
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10 A.M.
11 A.M.
12 NOON
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11 P.M.
12 NIGHT
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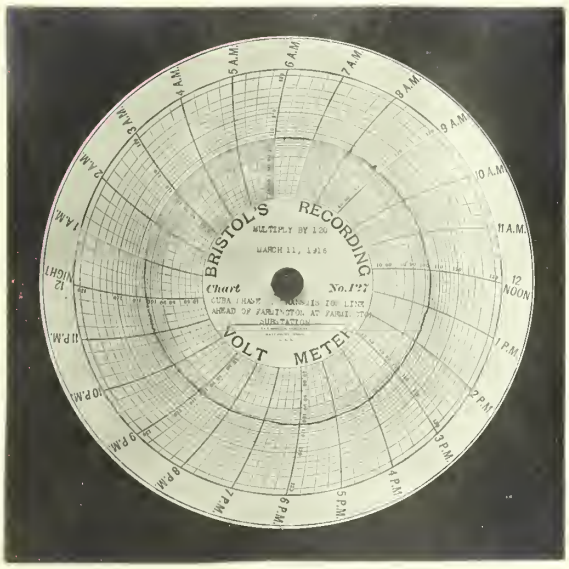
3 A.M.

Fig. 11


BRISTOL'S RECORDING
VOLT METER
Chart
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11 P.M.
12 NIGHT
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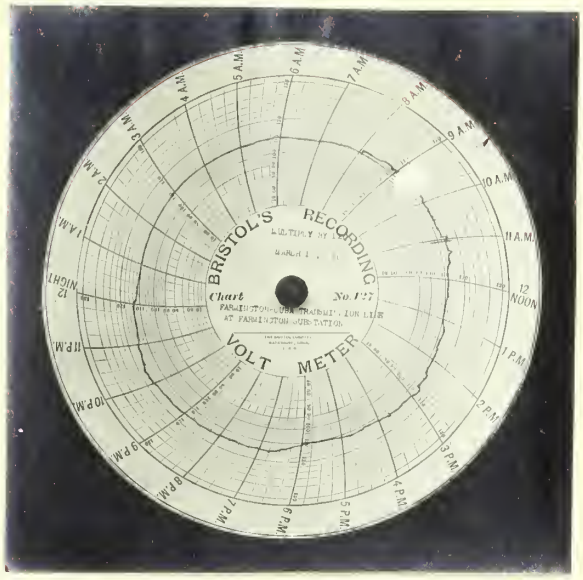
2 A.M.
3 A.M.

Fig. 12


BRISTOL'S RECORDING
VOLT METER
Chart
No. 127
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11 P.M.
12 NIGHT
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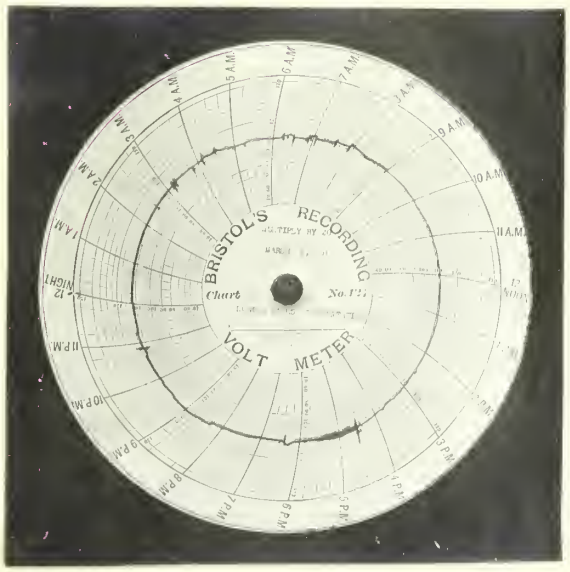
2 A.M.
3 A.M.

Fig. 13


BRISTOL'S RECORDING
VOLT METER
Chart
4 A.M.
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6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NIGHT
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2 A.M.
3 A.M.
11 P.M.
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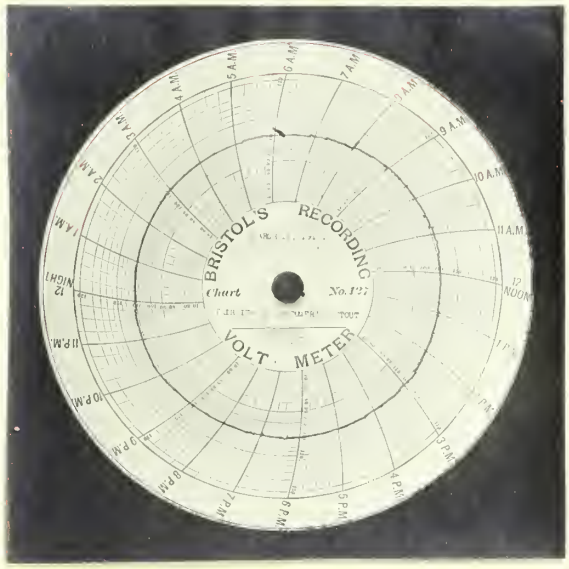
7 P.M.
6 P.M.
5 P.M.
4 P.M.

Fig. 14


BRISTOL'S RECORDING
VOLT METER
Chart
No. 127
4 A.M.
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7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
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4 P.M.
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9 P.M.
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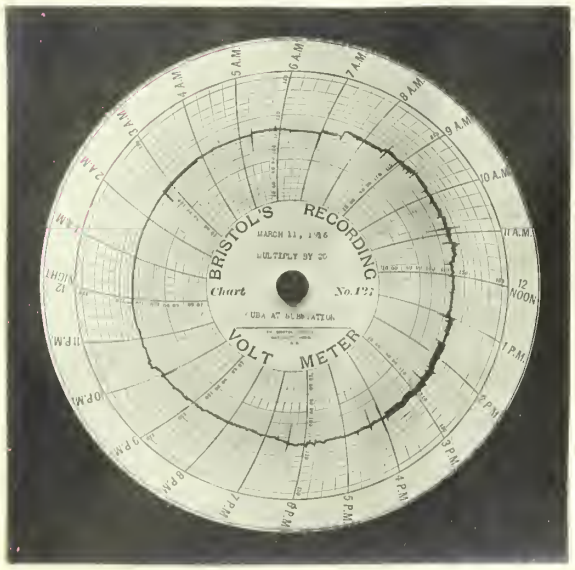
11 P.M.
12 NIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 15


BRISTOL'S RECORDING
VOLT METER
Chart
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10 A.M.
11 A.M.
12 NOON
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12 NIGHT
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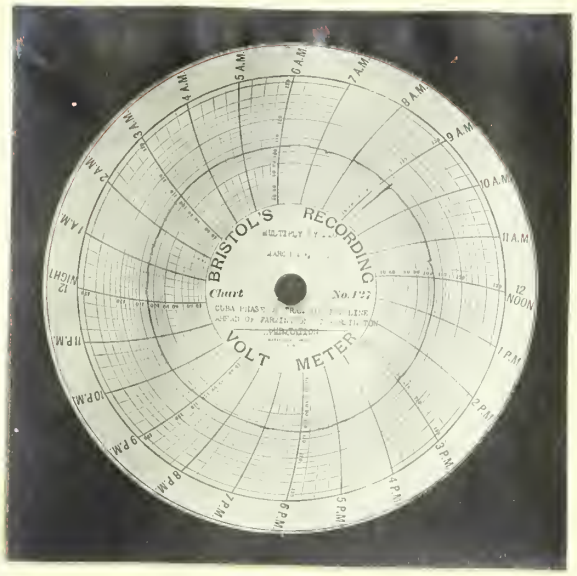
2 A.M.
3 A.M.

Fig. 16


BRISTOL'S RECORDING
VOLT METER
Chart
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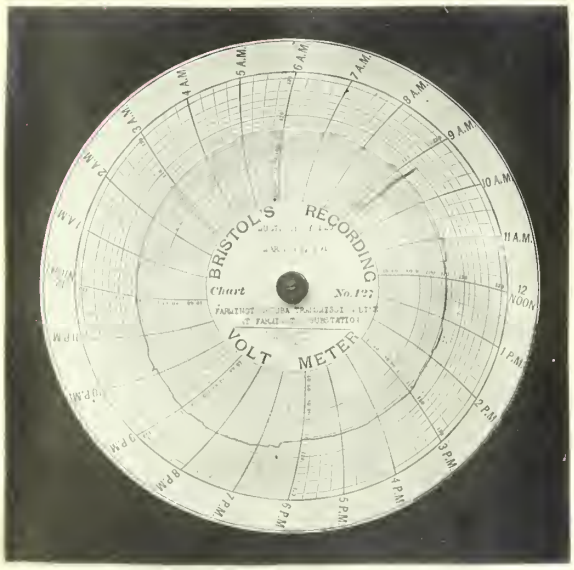
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 MIDNIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 17


BRISTOL'S RECORDING
VOLT METER
Chart
No. 127
4 A.M.
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11 A.M.
12 NOON
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7 P.M.
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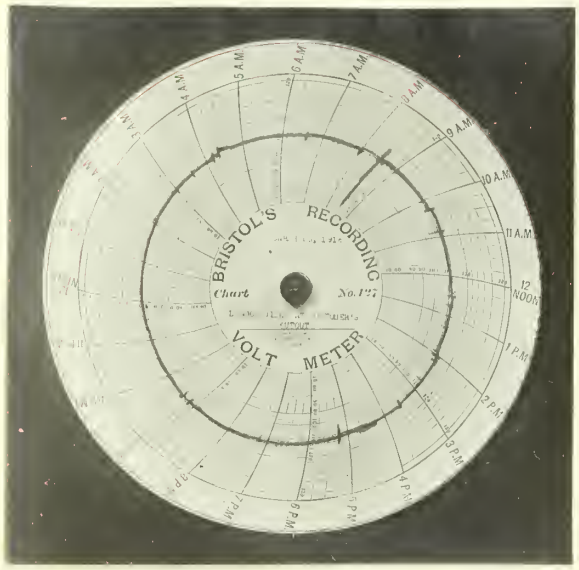
12 MIDNIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 18


BRISTOL'S RECORDING
Chart
No.127
VOLT METER
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
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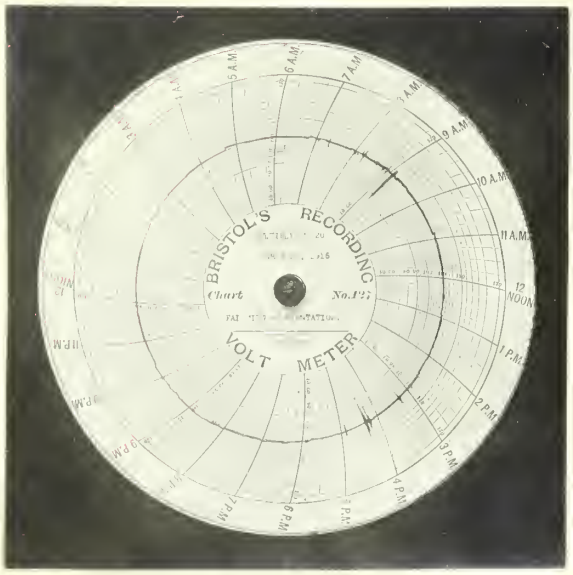
6 P.M.
7 P.M.

Fig. 19


BRISTOL'S RECORDING
Chart
No.127
VOLT METER
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
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7 P.M.

Fig. 20

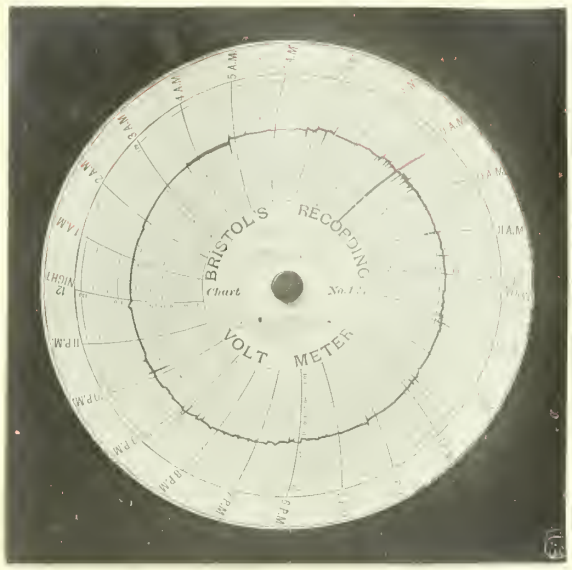
BRISTOL'S RECORDING
Chart
VOLT METER

Fig. 21

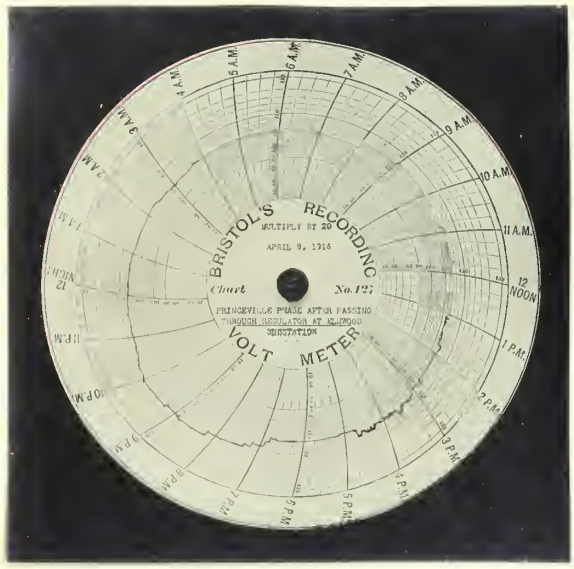
BRISTOL'S RECORDING
MULTIPLY BY 20
APRIL 9, 1916
Chart
No.127
PRINCEVILLE PHASE AFTER PASSING
THROUGH REGULATOR AT ELMWOOD
SUBSTATION
VOLT METER
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.

Fig. 22

BRISTOL'S
Chart
VOLT

Fig. 23

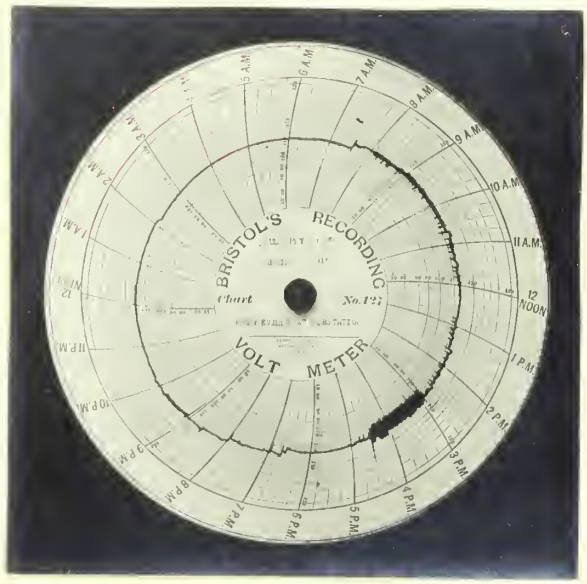
BRISTOL'S RECORDING
Chart
VOLT METER
5 A.M.
6 A.M.
7 A.M.
8 A.M.
9 A.M.
10 A.M.
11 A.M.
12 NOON
1 P.M.
2 P.M.
3 P.M.
4 P.M.
5 P.M.
6 P.M.
7 P.M.
8 P.M.
9 P.M.
10 P.M.
11 P.M.
12 M'NIGHT
1 A.M.
2 A.M.
3 A.M.

Fig. 24

the regulator at Farmington had reached its maximum boost and opened its limit switch before the maximum load had been reached. Fairview showed exactly 110 volts at customers cut out during the peak period. It must be realized that in order to regulate properly at Cuba, Fairview must raise slightly at the peak loads. This can be accomplished in two ways: either, by raising the voltage ahead of the regulator by means of the variable ratio taps in the step-down transformer at Farmington, or by raising the voltage at all towns by means of the variable ratio taps in the substation transformers. The regulator can then be adjusted for the proper light load voltage and the result will be an increase in available boost at the regulator. With the transformer ratios properly arranged, the normal full load voltage at Fairview would probably raise 1% and that at Cuba drop 1% as theoretically there should normally be less than 2% difference in voltage between these two towns. This is all distinctly borne out in Figs. 20 and 21 where it is to be noted that on Monday evening, March 13, with a considerably lighter load than the previous Saturday evening, the raise during the peak period at Fairview was 1.8%, while that at Cuba was approximately 0.9%. These charts also indicate that the line drop compensator of the regulator at Farmington was set at slightly too high a value.

IX.

RESULTS OBTAINED, FROM THE VIEWPOINT OF REVENUE INCOME

Assuming the August and September loads of the two systems under discussion the average for the year and a 5% drop in voltage over the peak period, assumed two hours in duration, we can gain a fair knowledge of the loss in revenue occasioned by the poor regulation as it existed before the installation of regulators. Operating Mazda lamps at 95% rated voltage reduces their wattage 8% and their candle power 17%. The changes in carbon lamps are even more marked, the reduction being 10% and 25% respectively. With 148 kw. delivered to the two systems at an efficiency of 90% to the customers' cut outs, 133.3 kw. registered on the customers' meters. This value being reduced 8% due to low voltage, 11.5 kw. was lost. Under the above assumptions this loss amounted to 8395 kw.-hrs. per year. At 10¢ per kw.-hr. the monetary loss was $839.50 per year. Allowing 15% for interest, depreciation and maintenance, which is high for this class of equipment, the above loss would cover an investment of $5600. This does not take into account the loss occasioned through operating all line transformers 10% above rated voltage eighteen hours per day necessary to keep the peak load period voltage within reasonable limits. It also fails to take into account the improved service rendered the customers, the result of which can not be rated in dollars and cents, the value necessarily always remaining an uncapitalized asset.

X

CONCLUSIONS

The conclusions to be drawn from these investigations may be summarized as follows:

(1)- Transformer regulation plays an important part in the matter of voltage regulation at the customer's cut-out.

(2)- Transformer regulation is twice as bad under a 90% power factor load than under a load having 100% power factor.

(3)- The peak load power factor of transmission systems supplying small rural towns is near 90%.

(4)- The light load power factor of the same towns is very low, usually around 30%.

(5)- The installation of feeder voltage regulators pays from the investment standpoint.

(6)- Feeder voltage regulators installed in the manner described will not entirely compensate a drop in any particular town if caused by a sudden application of load in this particular town, such as might occur if a large motor were started; but heavy power load is not encountered in these districts. The power which is connected is not operated at

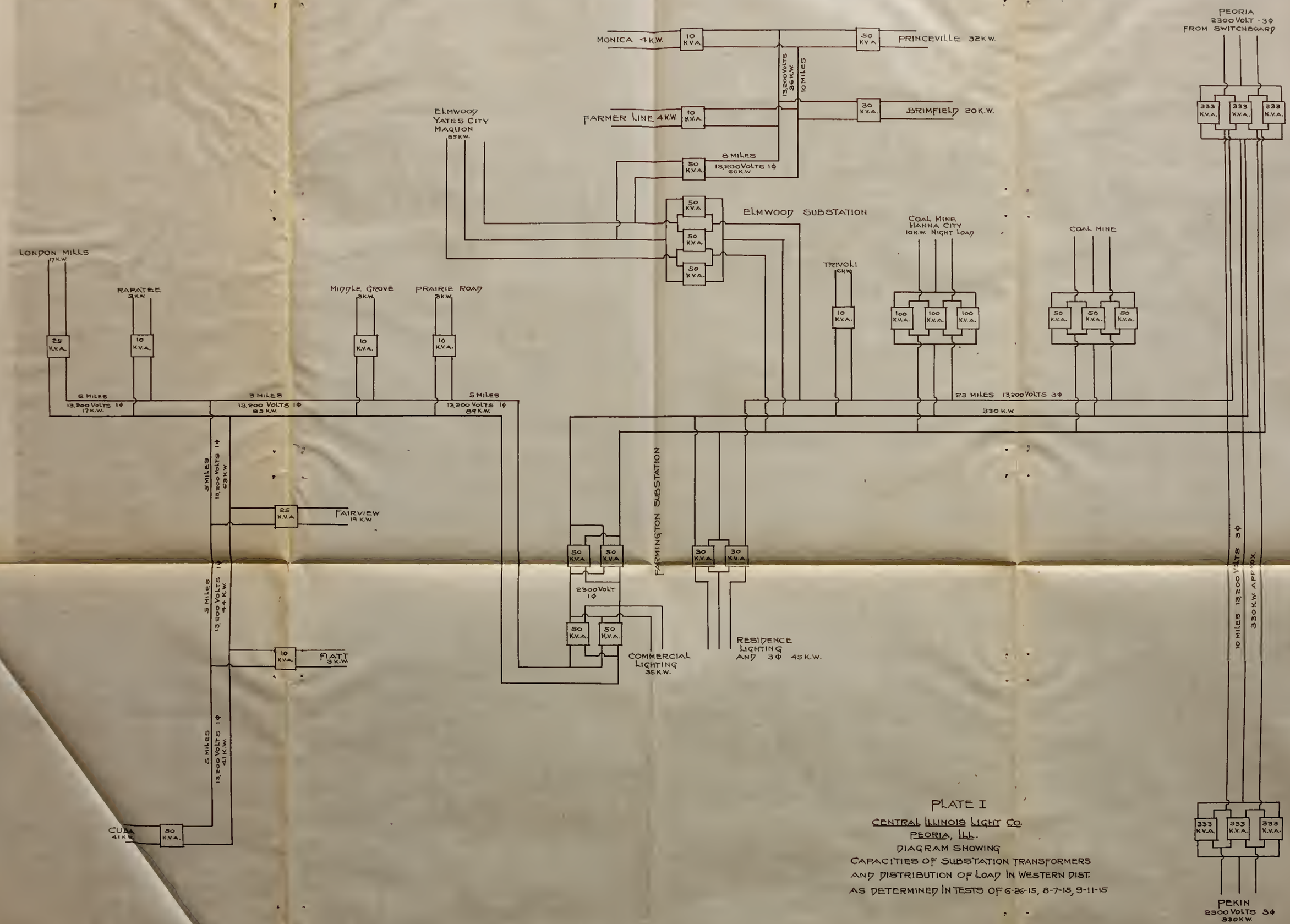

PLATE I

CENTRAL ILLINOIS LIGHT CO.

PEORIA, ILL.

DIAGRAM SHOWING

CAPACITIES OF SUBSTATION TRANSFORMERS

AND DISTRIBUTION OF LOAD IN WESTERN DIST.

AS DETERMINED IN TESTS OF 6-26-15, 8-7-15, 9-11-15

UNIVERSITY OF ILLINOIS-URBANA
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